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## Dark matter reflection of particle symmetry

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In the context of the relationship between physics of cosmological dark matter and symmetry of elementary particles a wide list of dark matter candidates is possible. New symmetries provide stability of different new particles and their combination can lead to a multicomponent dark matter. The pattern of symmetry breaking involves phase transitions in very early Universe, extending the list of candidates by topological defects and even primordial nonlinear structures.

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### 1. Introduction

The structure and interactions of known particles are described on the basis of the principle of gauge symmetry of the Standard model, extending invariance of quantum electrodynamics relative to gauge transformations to symmetry of strong and weak interactions. This approach assumes symmetry between different particles and ascribes their difference to the mechanisms of symmetry breaking. However, the Standard model (SM), successfully describing properties and interactions of the known particles, is not sufficient to provide the basis for the modern inflationary cosmology with baryosynthesis and dark matter/energy, as well as it should be extended to resolve its internal problems like divergence of the mass of the Higgs boson or problem of CP violation in Quantum Chromodynamics (QCD). The possibility to unify strong and electroweak interactions in the framework of Grand Unified Theories (GUT) adds an aesthetical argument to extend the SM. The discovery of nonzero mass of neutrino has already moved physics beyond the SM, in which neutrinos are massless.

Extensions of the standard model involve new symmetries and new particle states. Noether's theorem relates the exact particle symmetry to conservation of the respective charge. If the symmetry is strict, the charge is strictly conserved and the lightest particles bearing it are stable. Born in the early Universe they should

be present now around us. Their absence means that they should be elusive, being a form of cosmological dark matter. It links new symmetries of micro world to their dark matter signatures.

Symmetry breaking induces new fundamental physical scales in particle theory. If the symmetry is spontaneously broken, it is restored, when the temperature exceeds the corresponding scale. In the course of cosmological expansion the temperature decreased and the transition to the phase with broken symmetry took place. depending on the symmetry breaking pattern, to formation of topological defects in very early Universe. Defects can represent new forms of stable particles (as it is in the case of magnetic monopoles<sup>1-3</sup>), or extended macroscopic structures as cosmic strings<sup>4,5</sup> or cosmic walls.<sup>6</sup> Even unstable defects can leave replica in primordial nonlinear structures that remain in the Universe after the structure of defects decay (see below Sec.3 and Ref.7 for recent review). Here we give a brief review of various forms of dark matter reflections of particle symmetry.

## 2. Stable particles

Most of the known particles are unstable. For a particle with the mass  $m$  the particle physics time scale is  $t \sim 1/m$ <sup>a</sup>, so in particle world we refer to particles with lifetime  $\tau \gg 1/m$  as to metastable. To be of cosmological significance in the Big Bang Universe metastable particle should survive after  $t \sim (m_{Pl}/m^2)$ , when the temperature of the Universe  $T$  fell down below  $T \sim m$  and particles go out of thermal equilibrium. It means that the particle lifetime should exceed  $t \sim (m_{Pl}/m) \cdot (1/m)$  and such a long lifetime should be explained by the existence of a symmetry. From this viewpoint, physics of dark matter is sensitive to the conservation laws reflecting strict or nearly strict symmetries of particle theory.

### 2.1. *Weakly interacting massive particle miracle*

The simplest form of dark matter candidates is the gas of new stable neutral massive particles, originated from early Universe. Their stability can be protected by some discrete (as R-parity in supersymmetry) or continuous symmetry.

For particles with the mass  $m$ , at high temperature  $T > m$  the equilibrium condition,  $n \cdot \sigma v \cdot t > 1$  is valid, if their annihilation cross section  $\sigma > 1/(mm_{Pl})$  is sufficiently large to establish the equilibrium. At  $T < m$  such particles go out of equilibrium and their relative concentration freezes out. If particles have mass in the range of tens-hundreds GeV and annihilation cross section corresponding to weak interaction, the primordial frozen out abundance of such Weakly Interacting Massive Particles (WIMPs) can explain the observed dark matter density. This is the main idea of the so called *WIMP miracle* (see e.g. Refs. 8–11 for details).

The process of WIMP annihilation to ordinary particles, considered in  $t$ -channel, determines their scattering cross section on ordinary particles and thus relates the

<sup>a</sup>Here and further, if it isn't specified otherwise we use the units  $\hbar = c = k = 1$

primordial abundance of WIMPs to their scattering rate in the ordinary matter. Forming nonluminous massive halo of our Galaxy, WIMPs can penetrate the terrestrial matter and scatter on nuclei in underground detectors. The strategy of direct WIMP searches implies detection of recoil nuclei from this scattering.

The process inverse to annihilation of WIMPs corresponds to their production in collisions of ordinary particles. It should lead to effects of missing mass and energy-momentum, being the challenge for experimental search for production of dark matter candidates at accelerators, e.g. at LHC.

## 2.2. *Super-WIMPs*

The maximal temperature, which is reached in inflationary Universe, is the reheating temperature,  $T_r$ , after inflation. So, the very weakly interacting particles with the annihilation cross section  $\sigma < 1/(T_r m_{Pl})$ , as well as very heavy particles with the mass  $m \gg T_r$  can not be in thermal equilibrium, and the detailed mechanism of their production should be considered to calculate their primordial abundance.

In particular, thermal production of gravitino in very early Universe is proportional to the reheating temperature  $T_r$ , what puts upper limit on this temperature from constraints on primordial gravitino abundance.<sup>16–22</sup>

## 3. Global U(1) symmetry

A wide class of particle models possesses a symmetry breaking pattern, which can be effectively described by pseudo-Nambu–Goldstone (PNG) field (see Refs. 10, 23, 24 for review and references). The coherent oscillations of this field represent a specific type of cold dark matter (CDM) in spite of a very small mass of PNG particles  $m_a = \Lambda^2/f$ , where  $f \gg \Lambda$ , since these particles are created in Bose-Einstein condensate in the ground state, i.e. they are initially created as nonrelativistic in the very early Universe. This feature, typical for invisible axion models can be the general feature for all the axion-like PNG particles.

At high temperatures the pattern of successive spontaneous and manifest breaking of global U(1) symmetry implies the succession of second order phase transitions. In the first transition at  $T \sim f$ , continuous degeneracy of vacua leads, at scales exceeding the correlation length, to the formation of topological defects in the form of a string network; in the second phase transition at  $T \sim \Lambda \ll f$ , continuous transitions in space between degenerated vacua form surfaces: domain walls surrounded by strings. This last structure is unstable, but, as was shown in the example of the invisible axion,<sup>25–27</sup> it is reflected in the large scale inhomogeneity of distribution of energy density of coherent PNG (axion) field oscillations. This energy density is proportional to the initial value of phase, which acquires dynamical meaning of amplitude of axion field, when axion mass  $m_a = C m_\pi f_\pi / f$  (where  $m_\pi$  and  $f_\pi \approx m_\pi$  are the pion mass and constant, respectively, the constant  $C \sim 1$  depends on the choice of the axion model and  $f \gg f_\pi$  is the scale of the Peccei-Quinn symmetry breaking) is switched on in the result of the second phase transition.

The value of phase changes by  $2\pi$  around string. This strong nonhomogeneity of phase leads to corresponding nonhomogeneity of energy density of coherent PNG (axion) field oscillations. Usual argument (see e.g. Ref. 28 and references therein) is essential only on scales, corresponding to mean distance between strings. This distance is small, being of the order of the scale of cosmological horizon in the period, when PNG field oscillations start. However, since the nonhomogeneity of phase follows the pattern of axion string network this argument misses large scale correlations in the distribution of oscillations' energy density.

Indeed, numerical analysis of string network (see review in the Ref. 29) indicates that large string loops are strongly suppressed and the fraction of about 80% of string length, corresponding to long loops, remains virtually the same in all large scales. This property is the other side of the well known scale invariant character of string network. Therefore the correlations of energy density should persist on large scales, as it was revealed in Refs. 25–27. Discussion of such primordial inhomogeneous structures of dark matter go beyond the scope of the present paper and we can recommend the interested reader Refs. 10, 23, 24 for review and references.

#### 4. New gauge symmetries

Extensive hidden sector of particle theory can provide the existence of new interactions, which only new particles possess. Historically one of the first examples of such self-interacting dark matter was presented by the model of mirror matter. Mirror particles, first proposed in Ref. 30 to restore equivalence of left- and right-handed co-ordinate systems, represent a new set of symmetric partners for ordinary quarks and leptons<sup>31</sup> with their own strong, electromagnetic and weak mirror interactions. It means that there should exist mirror quarks, bound in mirror nucleons by mirror QCD forces and mirror atoms, in which mirror nuclei are bound with mirror electrons by mirror electromagnetic interaction.<sup>32,33</sup> If gravity is the only common interaction for ordinary and mirror particles, mirror matter can be present in the Universe in the form of elusive mirror objects, having symmetric properties with ordinary astronomical objects (gas, plasma, stars, planets...), but causing only gravitational effects on the ordinary matter.<sup>34,35</sup>

Even in the absence of any other common interaction except for gravity, the observational data on primordial helium abundance and upper limits on the local dark matter seem to exclude mirror matter, evolving in the Universe in a fully symmetric way in parallel with the ordinary baryonic matter.<sup>36,37</sup> The symmetry in cosmological evolution of mirror matter can be broken either by initial conditions,<sup>38,39</sup> or by breaking mirror symmetry in the sets of particles and their interactions as it takes place in the shadow world,<sup>40,41</sup> arising in the heterotic string model. We refer to Refs. 9, 42, 43 for current review of mirror matter and its cosmology.

If new particles possess new  $y$ -charge, interacting with massless bosons or intermediate bosons with sufficiently small mass ( $y$ -interaction), for slow  $y$ -charged particles Coulomb-like factor of "Gamov-Sommerfeld-Sakharov enhancement"<sup>44–46</sup>

should be added in the annihilation cross section

$$C_y = \frac{2\pi\alpha_y/v}{1 - \exp(-2\pi\alpha_y/v)},$$

where  $v$  is relative velocity and  $\alpha_y$  is the running gauge constant of  $y$ -interaction. This factor may not be essential in the period of particle freezing out in the early Universe (when  $v$  was only few times smaller than  $c$ ), but can cause strong enhancement in the effect of annihilation of nonrelativistic dark matter particles in the Galaxy. Products of annihilation contribute fluxes of cosmic rays and/or cosmic gamma radiation, giving a sensitive probe for even subdominant dark matter component.<sup>47, 48</sup>

## 5. Approximate symmetries

### 5.1. *Decaying dark matter*

Decaying particles with lifetime  $\tau$ , exceeding the age of the Universe,  $t_U$ ,  $\tau > t_U$ , can be treated as stable. By definition, primordial stable particles survive to the present time and should be present in the modern Universe. The net effect of their existence is given by their contribution into the total cosmological density. However, even small effect of their decay can lead to significant contribution to cosmic rays and gamma background.<sup>49</sup> Leptonic decays of dark matter are considered as possible explanation of the cosmic positron excess, measured in the range above 10 GeV by PAMELA,<sup>50</sup> FERMI/LAT<sup>51</sup> and AMS02.<sup>52</sup>

Primordial unstable particles with the lifetime, less than the age of the Universe,  $\tau < t_U$ , can not survive to the present time. But, if their lifetime is sufficiently large to satisfy the condition  $\tau \gg (m_{Pl}/m) \cdot (1/m)$ , their existence in early Universe can lead to direct or indirect traces.<sup>53</sup>

Weakly interacting particles, decaying to invisible modes, can influence Large Scale Structure formation. Such decays prevent formation of the structure, if they take place before the structure is formed. Invisible products of decays after the structure is formed should contribute in the cosmological dark energy. The Unstable Dark matter scenarios<sup>54–62</sup> implied weakly interacting particles that form the structure on the matter dominated stage and then decay to invisible modes after the structure is formed.

Cosmological flux of decay products contributing into the cosmic and gamma ray backgrounds represents the direct trace of unstable particles.<sup>53, 63</sup> If the decay products do not survive to the present time their interaction with matter and radiation can cause indirect trace in the light element abundance<sup>18–20, 64</sup> or in the fluctuations of thermal radiation.<sup>65</sup>

### 5.2. *Charge asymmetry of dark matter*

The fact that particles are not absolutely stable means that the corresponding charge is not strictly conserved and generation particle charge asymmetry is pos-

sible, as it is assumed for ordinary baryonic matter. At sufficiently strong particle annihilation cross section excessive particles (antiparticles) can dominate in the relic density, leaving exponentially small admixture of their antiparticles (particles) in the same way as primordial excessive baryons dominate over antibaryons in baryon asymmetric Universe. In this case *Asymmetric dark matter* doesn't lead to significant effect of particle annihilation in the modern Universe and can be searched for either directly in underground detectors or indirectly by effects of decay or condensation and structural transformations of e.g. neutron stars (see Ref. 66 for recent review and references). If particle annihilation isn't strong enough, primordial pairs of particles and antiparticles dominate over excessive particles (or antiparticles) and this case has no principle difference from the charge symmetric case. In particular, for very heavy charged leptons (with the mass above 1 TeV), like "tera electrons",<sup>67</sup> discussed in 6.1, their annihilation due to electromagnetic interaction is too weak to provide effective suppression of primordial tera electron-positron pairs relative to primordial asymmetric excess.<sup>68</sup>

## 6. Dark atoms

New particles with electric charge and/or strong interaction can form anomalous atoms and contain in the ordinary matter as anomalous isotopes. For example, if the lightest quark of 4th generation (that possess new conserved charge) is stable, it can form stable charged hadrons, serving as nuclei of anomalous atoms of e.g. anomalous helium.<sup>68–73</sup> Therefore, stringent upper limits on anomalous isotopes, especially, on anomalous hydrogen put severe constraints on the existence of new stable charged particles. However, as we discuss in the rest of this review, stable doubly charged particles can not only exist, but even dominate in the cosmological dark matter, being effectively hidden in neutral "dark atoms".<sup>74</sup>

### 6.1. Charged constituents of Dark Atoms

New stable particles may possess new U(1) gauge charges and bind by Coulomb-like forces in composite dark matter species. Such dark atoms cannot be luminous, since they radiate invisible light of U(1) photons. Historically mirror matter (see subsection 4 and Refs. 8, 42 for review and references) seems to be the first example of such an atomic dark matter.

However, it turned out that the possibility of new stable electrically charged leptons and quarks is not completely excluded and Glashow's tera-helium<sup>67</sup> has offered a new solution for this type of dark atoms of dark matter. Tera-*U*-quarks with electric charge  $+2/3$  formed stable (*UUU*)  $+2$  charged "clusters" that formed with two  $-1$  charged tera-electrons *E* neutral [*(UUU)EE*] tera-helium "atoms" that behaved like Weakly Interacting Massive Particles (WIMPs). The main problem for this solution was to suppress the abundance of positively charged species bound with ordinary electrons, which behave as anomalous isotopes of hydrogen or helium. This problem turned to be unresolvable,<sup>68</sup> since the model<sup>67</sup> predicted stable

tera-electrons  $E^-$  with charge -1. As soon as primordial helium is formed in the Standard Big Bang Nucleosynthesis (SBBN) it captures all the free  $E^-$  in positively charged  $(HeE)^+$  ion, preventing any further suppression of positively charged species. Therefore, in order to avoid anomalous isotopes overproduction, stable particles with charge -1 (and corresponding antiparticles) should be absent, so that stable negatively charged particles should have charge -2 only.

Elementary particle frames for heavy stable -2 charged species are provided by: (a) stable "antibaryons"  $\bar{U}\bar{U}\bar{U}$  formed by anti- $U$  quark of fourth generation<sup>72–76</sup> (b) AC-leptons,<sup>71,74</sup> predicted in the extension<sup>71</sup> of standard model, based on the approach of almost-commutative geometry.<sup>77</sup> (c) Technileptons and anti-technibaryons<sup>78</sup> in the framework of walking technicolor models (WTC).<sup>79–84</sup> (d) Finally, stable charged clusters  $\bar{u}_5\bar{u}_5\bar{u}_5$  of (anti)quarks  $\bar{u}_5$  of 5th family can follow from the approach, unifying spins and charges.<sup>85</sup> Since all these models also predict corresponding +2 charge antiparticles, cosmological scenario should provide mechanism of their suppression, what can naturally take place in the asymmetric case, corresponding to excess of -2 charge species,  $O^{--}$ . Then their positively charged antiparticles can effectively annihilate in the early Universe.

If new stable species belong to non-trivial representations of electroweak  $SU(2)$  group, sphaleron transitions at high temperatures can provide the relationship between baryon asymmetry and excess of -2 charge stable species, as it was demonstrated in the case of WTC in Refs. 78, 86–90.

## 7. Multicomponent Dark Matter

Higher symmetry extensions of SM can embed various forms of dark matter candidates in a unique theoretical framework.

Broken  $SU(3)_H$  family symmetry not only described the existence and observed properties of the three known quark-lepton families<sup>59,60,91,92</sup> (see also<sup>93–95</sup>), but also provided the physical mechanisms for inflation and baryosynthesis as well as it offered unified description of axion and massive neutrinos - candidates for Cold, Warm, Hot and Unstable Dark Matter. The parameters of axion cold dark matter (CDM), as well as the masses and lifetimes of neutrinos corresponded to the hierarchy of breaking of the  $SU(3)_H$  symmetry of families, fixing their relative contribution into the total density. This approach gave a flavor of a quantitatively definite multi-component dark matter scenarios and elaborated the method to treat such multi-parameter models in an over-determined set of their physical, astrophysical and cosmological probes. It was considered as a bottom-up approach to heterotic string phenomenology, in which all the richness of possible dark matter candidates can find their proper place.<sup>54</sup>

Indeed  $E_8 \times E'_8$  model combines supersymmetric candidates, 248 gauge bosons of  $E'_8$  new interactions together with the set of 248 fundamental particles of shadow world. Embedding SM symmetry it can also contain additional quark-lepton family with its new gauge  $U(1)$  interaction.<sup>96,97</sup> Compactification of extra dimensions can

lead to existence of homotopically stable objects.<sup>98</sup> Multiple Kaluza-Klein (KK) dark matter candidates arise naturally in generic Type-IIB string theory compactification scenarios.<sup>99</sup> Treatment of such multi-parameter space needs special methods developed by cosmoparticle physics.

## 8. Towards cosmoparticle physics of dark matter

The widely discussed complementarity of direct and indirect dark matter searches represents the simplest example of general methods of cosmoparticle physics, studying the fundamental basis and mutual relationship between micro- and macro-worlds in the proper combination of physical, astrophysical and cosmological signatures.<sup>8,9,100,101</sup> Methods of cosmoparticle physics confronting the multi-parameter space of new phenomena, predicted by particle theory, with the over-determined set of their physical, astrophysical and cosmological probes can give in their development clear answer on the true picture of the Universe and physical laws, on which it is based. In particular, it will shed light on the problem of cosmological dark matter in the context of the fundamental structure of the microworld.

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